The Scale Dependence of Inclusive *ep* Scattering in the Resonance Region.

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Abstract

We examine the scale dependence in the resonance region of inclusive *ep* scattering. In particular we discuss the invariants other than Q^2, which have been proposed as a scale for pQCD evolution in a kinematical regime where both infrared singularities and power corrections are expected to be largest. We show that the region where most of the present data are available, can be described using NLO pQCD evolution at fixed invariant mass, W^2, plus a leading order power correction term. We find that the coefficient of the power correction at $W^2 < 4\,GeV^2$ is relatively small, *i.e.* comparable in size to the one obtained in the large W^2 region.

It has been long known that a fully quantitative description of proton structure in terms of parton distribution functions must account for power corrections to the Q^2 dependence of the data, in addition to the predicted perturbative-QCD (pQCD) behavior. Power corrections are indeed observed in experiments as discrepancies between fixed order perturbative predictions and the data. Their theoretical interpretation is however a less well defined issue. In Deep Inelastic Scattering (DIS), in particular, the short-distance scattering involving single, non-interacting partons is expected to give way to

processes in which two (or more) quarks or gluons participate simultaneously in the scattering. These processes correspond formally to the Higher Twist (HT), or the higher order terms in the "twist" expansion (twist=dimension-spin) [2]. The coefficients of the HTs cannot be evaluated directly within perturbation theory. However, it is also known that power corrections should appear in the coefficient functions for hard processes, generated by the divergence of the perturbative series at large orders (renormalons) [3]. Whether in DIS the two kinds of power corrections can be distinguished from one another and compared to the data is still an open question (see however [4]).

In recent analyses the HT terms have been extracted from DIS data by applying a cut in the kinematics at $W^2 \geq 10\,\mathrm{GeV}^2$ [6, 4] (W^2 is the invariant mass of the final hadronic state), that is excluding the kinematical region dominated by nucleon resonances. Following [7, 8] we have shown [9, 10] however that the entire set of inclusive data, including the low W^2 region can be described by a pQCD based analysis, the contribution from HTs being overall relatively small, *i.e.* within a factor of two from the one obtained in [6, 4]. The observation of a small power contribution can be otherwise phrased in terms of "approximate Duality", namely the non-perturbative features of the data appearing as the characteristic peaks describing the nucleon resonances, average out to a curve that can be identified with the DIS one modulo perturbative corrections plus a small size power correction. Based on the results of [9, 10], we perform here a more accurate analysis in the low W^2 domain with the aim of understanding the origin of the *residual* inverse-powerlike Q^2 dependence of the data.

Our analysis is based on three observations:

(1) The recent Jefferson Lab data on the structure function F_2 [11] show "scaling" in W^2, *i.e.* invariance with W^2 of the smooth curves which average through the resonances peaks. The smooth fits to the data plotted vs. $\xi = (2x)/(1 + +4M^2x^2/Q^2)^{1/2}$, in order to account for target mass corrections, are shown in Fig.1 (dotted curves), for four different values of W^2 in the $W^2 \leq 4\,\mathrm{GeV}^2$ range. Fig.1 also shows that as W^2 increases some scaling violations are present. Eventually in the DIS region, *i.e.* at $W^2 \geq 4\,\mathrm{GeV}^2$, W^2-scaling breaks down completely. [1] We conclude that the data *scale in* W^2 so long as one one keeps inside the resonance region.

[1] This is due to the fact that the contribution of the fastly evolving sea quarks is no longer negligible.

(2) A pQCD based analysis is in principle possible in the resonance region (see also [7, 8, 9] so long as the values of Q^2 are larger than $\approx 1\,\mathrm{GeV}^2$. Because of the kinematical relation $W^2 = Q^2(1-x)/x + M^2$, M^2 being the nucleon mass, this constraint corresponds to large x values ($x \geq 0.2$ at present kinematics). In analyses of DIS F_2 can be written as:

$$F_2(\xi, Q^2) = F_2^{NLO}(\xi, Q^2)\left(1 + \frac{C(\xi, Q^2)}{Q^2}\right), \tag{1}$$

where $F_2^{NLO}(\xi, Q^2)$ is the NLO pQCD contribution and we disregard $O(1/Q^4)$ and higher terms. In order to try to reproduce W^2 scaling, we consider evolution at fixed W^2. In other words in Eq.(1) $Q^2 = Q^2(x) \equiv (W_R^2 - M^2)x/(1-x)$ where W_R is the fixed invariant mass of a given resonance. In our evolution equations we have used the recent PDFs from [1], in which $Q_o^2 \leq 1\,\mathrm{GeV}^2$. We limit our analysis to the large x region ($x \geq 0.2$) so that the Singlet contribution that might introduce some ambiguity for the evolution down to a low scale, is negligible. The results of perturbative evolution, determining F_2^{NLO} are presented in Fig.1 along with the fits to Jlab data. We note first of all that there is an evident mismatch: the PDF results exceed the experimental values at $x < 0.6$ and they lie lower at large x. Secondly pQCD evolution predicts a stronger evolution at fixed W^2.

Using Eq.(1) we interpret the discrepancies between perturbative evolution and the data as given by the leading non-perturbative contribution to the structure function. This actually enables us to determine the coefficient C from the data:

$$C(\xi, Q^2) = \frac{Q^2 \Delta F}{F_2^{NLO}(x, Q^2)}, \tag{2}$$

where

$$\Delta F = F_2^{NLO}(\xi, Q^2(x)) - F_2^{Exp}(x, Q^2(x)) \tag{3}$$

In Fig.2 we show $C(\xi, Q^2)$ vs. ξ. Our extractions are shown at different values of Q^2 (obtained by transforming back from the fixed W^2 values). For comparison the results from the analysis of [6] using only $W^2 > 10\,\mathrm{GeV}^2$ data are also shown (dotted curves). [2] Our results, which use only data at $W^2 \leq 4\,GeV^2$, are in astonishing agreement with the high mass ones. At

[2] Note: the appearence of a strong Q^2 dependence in the coefficient C is mainly due to the transformation $x \to \xi$.

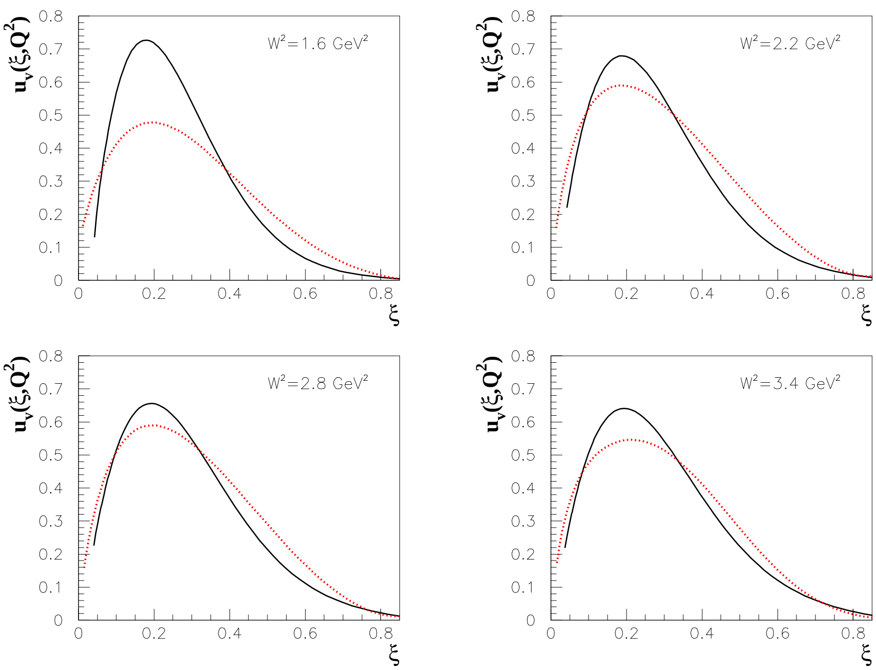

Fig.1

larger ξ however the value of $C(\xi, Q^2)$ becomes less clearly determined and as $\xi \to \xi_{th}$ (corresponding to $x \geq 0.8$) it is completely undefined. A possible interpretation of the indetermination at large ξ is that standard DGLAP evolution becomes unreliable and that evolution using a z-dependent scale should be performed instead [12]. A quantitative approach to this problem is pursued in [13]. However, we also observe that at large x data both in the large Q^2 region, determining F_2^{NLO}, and in the low W^2 region, determining $F_2^{Exp}(x, Q^2(x))$ in our analysis, are missing. Our analysis is extended to these regions by extrapolating what available at lower x and its results are clearly less reliable here. These regions would be accessible at the 12 GeV program at Jefferson Lab.

(3) Finally, we comment on the interpretation of the power corrections in the resonance region. From a practical point of view, if power corrections are found to mantain the same x dependence displayed in Fig.2, namely

$C \approx A/(1-x)$ as $x \to 1$, we predict that

$$R = \frac{C(x,Q^2)}{Q^2(x)} \to \frac{A}{W_R^2 - M^2}, \; x \to 1 \tag{4}$$

therefore at fixed W^2 one is approaching the $x \to 1$ limit and at the same time having control of the power correction terms. This situation is displayed in Fig.3 where we show R for different values of W^2. Not being dominated by power corrections, this region is ideal for pursuing further quantitative studies of deviations from NLO DGLAP evolution ([14] for earlier analyses and *e.g.* [15] for a more recent review).

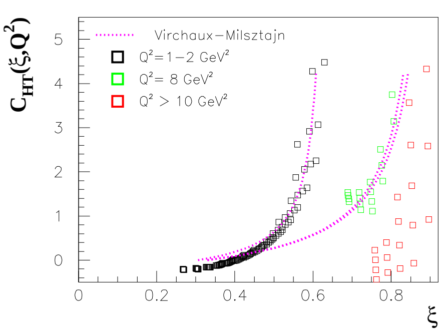

Fig.2

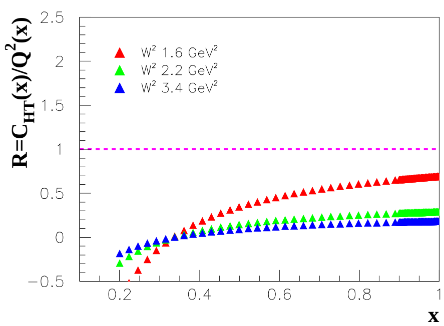

Fig.3

What is the physical meaning of a small power correction in the resonance region? Power corrections might originate from the account of multi parton "final state interaction" processes that are more likely to occur at large distances and that correspond to well defined terms in the OPE. It is this type of interactions that are eventually responsible for confinement related features of the cross section such as the production of resonances. It turns out that for some, at present, unknown mechanism, the HTs contributions of increasing order in $1/Q^2$ cancel each other in the resonance region, giving origin to the duality phenomenon (this is seen either in the average, Fig.1, or in the moments integrals [7]). However we find out through an accurate analysis of the data that duality is not exact: a "residual" $1/Q^2$ dependence with a coefficient comparable to the large W^2 analyses [6] is still necessary to interpret the data. This Q^2 dependence not being ascribed to HT corrections,

can be taken as the true contribution from the non-perturbative corrections to the pQCD coefficient functions, namely the renormalon term. In order to confirm this interpretation, further studies addressed at determining the universality of this correction should be performed. These would include studies of different structure functions, such as F_L in the resonance region, as well as scattering from different targets, including nuclei and studies of different fragmentation functions, a program accessible at Jefferson Lab at 12 GeV.

On a more speculative level, the interpretation of the physical picture behind this behavior leads to a number of intriguing scenarios: for instance, partons inside hadrons might be arranged in a different way at intermediate/large-distances, *e.g.* they might be clumped together inside valence quarks and the role of final state interactions might be effectively small down to low Q^2.

In conclusion, information on the structure of the proton is still abundantly missing. It could be obtained if more data were available in the "transition" regions of x and Q^2 where perturbative QCD (pQCD) evolution regulated by DGLAP equations can no longer be considered to be the main mechanism, and non-perturbative contributions become important.

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